CURVATURE CORRECTED BANDGAP CIRCUIT

Field of the Invention

The present invention relates to voltage reference circuits that are

5   temperature compensated. More particularly, the present invention relates to a method

and apparatus for compensating the curvature effects in a band-gap reference circuit.

Background of the Invention

Band-gap voltage references are used as voltage references in electronic

systems. The energy band-gap of Silicon is on the order of 1.2V, and is independent

10   from temperature and power-supply variations. Bipolar transistors have a negative

temperature drift with respect to their base-emitter voltage (Vbe) such that their Vbe

decreases as the operating temperature increases on the order of -2mV/deg C. However,

the thermal voltage (Vt) of a bipolar transistor has a positive temperature drift (Vt =

kT/q) such that Vt increases as temperature increases. The positive temperature drift in

15   the thermal voltage (Vt) may be arranged to compensate the negative temperature drift

in the bipolar transistor's base-emitter voltage (Vbe). Band-gap reference circuits use

the inherent characteristics of bipolar transistors to compensate for temperature effects

and provide a stable operating voltage over various power-supply and temperature

ranges.

20   An example of a modern band-gap reference circuit is illustrated in

FIGURE 5. As shown in the figure, two bipolar transistors (Q1, Q2) are arranged with a

common base that is connected to VDD. Two resistors (R1, R2) are series connected

between the emitter of the first bipolar transistor (Q1) and the reference output (VOUT).

Another resistor (R3) is connected between the emitter of the second bipolar transistor

25   (Q2) and the reference output (VOUT). An error amplifier (EAMP) is used to adjust the

voltage of the reference output (VREF) through feedback. At steady-state, the voltage at

the common point of resistors R1 and R2 is the same as the voltage at the emitter of the

second bipolar transistor (Q2). The two bipolar transistors (Q1, Q2) are arranged to

provide a ten-to-one (10:1) current density difference with respect to one another (Q2 to

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Q1). The ten-to-one current density results in a 60mV difference between the base-emitter voltages of two bipolar transistors ($\Delta Vbe = Vt*\ln(A1/A2) = 26mV*\ln(10) = 60mV$, at room temperature. A1 and A2 are the respective emitter areas of bipolar transistors Q1 and Q2. Current I1 is set to equal current I2 by means of resistors R2, R3, and feedback operation of error amplifier EAMP. The 60mV difference appears across the first resistor (R1). The voltage between VDD and the output of the error amplifier corresponds to a reference voltage (VREF) that is given as $VREF = Vbe + X*Vt$, where X is a constant that is used to scale the temperature correction factor. The temperature correction factor (X) is adjusted by the ratio of the resistors $((R2/R1)*\ln(A1/A2))$. Typical temperature corrected reference voltages of 1.25V are achieved by this configuration.

Brief Description of the Drawings

Non-limiting and non-exhaustive embodiments of the present invention are described with reference to the following drawings.

FIGURE 1 is an illustration of an example curvature corrected band-gap circuit;

FIGURE 2 is an illustration of another example curvature corrected band-gap circuit;

FIGURE 3 is an illustration of yet another example curvature corrected band-gap circuit; and

FIGURE 4 is an example waveform for a curvature corrected band-gap circuit, arranged in accordance with an aspect of the present invention.

FIGURE 5 is an illustration of a conventional band-gap circuit.

FIGURE 6 is an example waveform for a conventional band-gap circuit.

Detailed Description of the Preferred Embodiment

Various embodiments of the present invention will be described in detail with reference to the drawings, where like reference numerals represent like parts and assemblies throughout the several views. Reference to various embodiments does not limit the scope of the invention, which is limited only by the scope of the claims

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attached hereto. Additionally, any examples set forth in this specification are not intended to be limiting and merely set forth some of the many possible embodiments for the claimed invention.

Throughout the specification and claims, the following terms take at least the meanings explicitly associated herein, unless the context clearly dictates otherwise. The meanings identified below are not intended to limit the terms, but merely provide illustrative examples for the terms. The meaning of "a," "an," and "the" includes plural reference, the meaning of "in" includes "in" and "on." The term "connected" means a direct electrical connection between the items connected, without any intermediate devices. The term "coupled" means either a direct electrical connection between the items connected or an indirect connection through one or more passive or active intermediary devices. The term "circuit" means either a single component or a multiplicity of components, either active and/or passive, that are coupled together to provide a desired function. The term "signal" means at least one current, voltage, charge, temperature, data, or other signal.

Briefly stated, the invention is related to an apparatus and method for providing curvature correction to the temperature variations in a band-gap reference circuit. The apparatus includes a band-gap cell, an IPTAT circuit, a resistor, and a feedback circuit. The band-gap cell is arranged to provide a band-gap voltage. The resistor circuit is coupled to both the band-gap cell and the IPTAT circuit. The feedback circuit is arranged to selectively activate the IPTAT circuit such that an additional correction factor is added to the temperature response of the band-gap cell to provide a second order curve. The IPTAT circuit can be implemented as a simple transistor that is responsive to changes in absolute temperature. The second-order temperature corrected curves have improved operating temperature ranges with minimal voltage variations when compared to a conventional band-gap circuit.

Typical CMOS band-gap circuits have output voltages that are temperature independent only to a first order. At some critical temperature, the band-gap voltage corresponds to a maximum value. However, at temperatures above and below the critical temperature the band-gap circuit exhibits second order effects that

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result in non-linear changes in the band-gap voltage. The non-linear effects are observable as a curvature in the temperature response of the band-gap voltage. The present invention provides a simple method to correct the output voltage curvature effect as will be described below.

5   FIGURE 1 is an illustration of an example curvature corrected band-gap circuit (100) that is arranged in accordance with an aspect of the present invention. Circuit 100 includes a band-gap cell, a feedback circuit, an IPTAT (current proportional to absolute temperature) circuit, and a resistor circuit. The band-gap cell is arranged to provide a band-gap voltage (VBG), and operates with a current (I1). The feedback

10   circuit is arranged to sense the band-gap voltage (VBG) and provide a detection signal (VDET). The IPTAT circuit is activated in response to the detection signal (VDET) and is arranged to provide another current (I2). Resistor R is coupled between the band-gap cell and a power supply voltage (VSUPPLY). A total current (ITOTAL) flows through resistor R that is related to currents I1 and I2. The band-gap voltage (VBG) is

15   related to the total current flowing through resistor R as will be described in further detail below.

          FIGURE 2 is an illustration of another example curvature corrected band-gap circuit (200) that is arranged in accordance with aspects of the present invention. Circuit 200 is substantially the same in operation as circuit 100, with further

20   detailed functional blocks as will be described.

          In circuit 200, the band-gap cell is illustrated as transistors Q1 and Q2, resistors R1 - R3, and error amplifier A1; resistor R is illustrated as resistor R4; the feedback circuit is illustrated as resistors R6 and R7; and the IPTAT circuit is illustrated as resistor R5 and transistor Q3. The supply voltage corresponds to VSS for this

25   example circuit.

          Transistor Q1 is a diode connected PNP device that has an emitter that is coupled to the non-inverting input of error amplifier A1. Transistor Q2 is another diode connected PNP device that has an emitter that is coupled to the inverting input of error amplifier A1 through resistor R1. Resistor R2 is coupled between resistor R4 and the

30   inverting input of amplifier A1, while resistor R3 is coupled between resistor R4 and

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the non-inverting input of error amplifier A1. Resistor R4 is also coupled to the output of error amplifier A1, which corresponds to the band-gap voltage of the circuit. Resistors R6 and R7 are arranged as a voltage divider that senses the band-gap voltage and provide a detection voltage (VDET). Transistor Q3 is a PNP transistor that has a collector that is coupled to the power supply voltage (VSS), an emitter that is coupled to resistor R4 through resistor R5, and a base that is responsive to the detection voltage (VDET).

In operation, transistor Q1 is arranged to conduct a first current that is designated as IQ1, and transistor Q2 is arranged to conduct a second current that is designated as IQ2. Since the band-gap voltage (VBG) is regulated through the feedback operation of error amplifier A1, the detection voltage (VDET) remains relatively unchanged over varied operating temperatures. The base-emitter voltage (VBE) of transistor Q3 is dependent on the absolute temperature of the circuit such that VBEQ3 decreases with increasing temperature. Consequently, transistor Q3 will remain inactive until the VBE decreases sufficient to forward bias transistor Q3. The detection voltage (VDET) is selected to adjust the temperature trip point for activating transistor Q3. Transistor Q3 is arranged to conduct a third current (IQ3), designated IQ3, when activated.

The band-gap cell is arranged such that currents IQ1 and IQ2 remain balanced according to the relative areas associated with transistors Q1 and Q2. In many band-gap cells, the ratio of the areas for transistors Q2 and Q1 corresponds to 10:1. For lower temperature, transistor Q3 is inactive and IQ3 is approximately zero. As the temperature increases, transistor Q3 will approach a temperature trip-point where it becomes forward biased. Once forward biased, the current through transistor Q3 will increase with increased temperature. Currents IQ1 - IQ3 are summed together through resistor R4 such that the band-gap voltage will increase once the temperature trip-point is reached for transistor Q3.

FIGURE 3 is an illustration of yet another example curvature corrected band-gap circuit (300) that is arranged in accordance with aspects of the present

invention. Circuit 300 is substantially the same in operation as circuit 100, with further detailed functional blocks as will be described.

In circuit 300, the band-gap cell is illustrated as transistors Q1 and Q2, resistors R1 - R3, and error amplifier A1; resistor R is illustrated as resistor R4; the
5   feedback circuit is illustrated as resistors R6 and R7; and the IPTAT circuit is illustrated as resistor R5 and transistor Q3. The supply voltage corresponds to VDD for this example circuit.

Transistor Q1 is a diode connected NPN device that has an emitter that is coupled to the non-inverting input of error amplifier A1. Transistor Q2 is another diode
10   connected NPN device that has an emitter that is coupled to the inverting input of error amplifier A1 through resistor R1. Resistor R2 is coupled between resistor R4 and the inverting input of amplifier A1, while resistor R3 is coupled between resistor R4 and the non-inverting input of error amplifier A1. Resistor R4 is also coupled to the output of error amplifier A1, which corresponds to the band-gap voltage of the circuit.
15   Resistors R6 and R7 are arranged as a voltage divider that senses the band-gap voltage and provide a detection voltage (VDET). Transistor Q3 is an NPN transistor that has a collector that is coupled to the power supply voltage (VDD), an emitter that is coupled to resistor R4 through resistor R5, and a base that is responsive to the detection voltage (VDET). The operation of circuit 300 is substantially similar to the operation of circuit
20   200, where the band-gap voltage is referenced from VDD instead of VSS.

FIGURE 4 is an example waveform for a curvature corrected band-gap circuit, arranged in accordance with an aspect of the present invention. In a first operating temperature range (e.g., -50°C through +50°C), the band-gap voltage (VBG) has a temperature corrected shape (400) that is similar to a typical band-gap circuit. In
25   a second operating temperature range (e.g., +50°C through +150°C), the bang-gap voltage (VBG) temperature response changes direction and begins increasing with increasing temperature. The overall temperature response of the band-gap circuit is improved since the operating temperature range is extended with minimal voltage variations when compared to a conventional band-gap circuit. FIGURE 4 illustrates

how the IPTAT circuit cooperates with the band-gap cell to provide an extended operating temperature range.

FIGURE 5 is an illustration of a conventional band-gap circuit. The balanced current operation in the conventional band-gap circuit provides for a temperature compensated band-gap voltage (VBG) as illustrated in FIGURE 6. The temperature compensated voltage has a curvature (600) that is concave (or convex) in shape such that the voltage variations are compensated over an operating temperature range. The curvature is intentionally designed with a single maxima point that is approximately centered over the operating temperature range. In contrast, the present invention has a maxima point and a minima point such that second order temperature effects are observed. In the present invention, the second order effects are intentionally provided to minimize the voltage variations over a wide operating temperature range.

The above specification, examples and data provide a complete description of the manufacture and use of the composition of the invention. Since many embodiments of the invention can be made without departing from the spirit and scope of the invention, the invention resides in the claims hereinafter appended.